The Lunar GNSS Receiver Experiment (LuGRE)

Joel J. K. Parker, NASA Goddard Space Flight Center
on behalf of the LuGRE team

January 26, 2022

The LuGRE Team

NASA

- **PI**: Joel Parker, NASA GSFC
- **Mission Manager**: Ben Anderson, NASA GSFC
- **Systems Engineer**: Steve McKim, NASA GSFC
- **Sponsor**: JJ Miller, NASA SCaN
- **Advisors**: Lisa Valencia, Frank Bauer

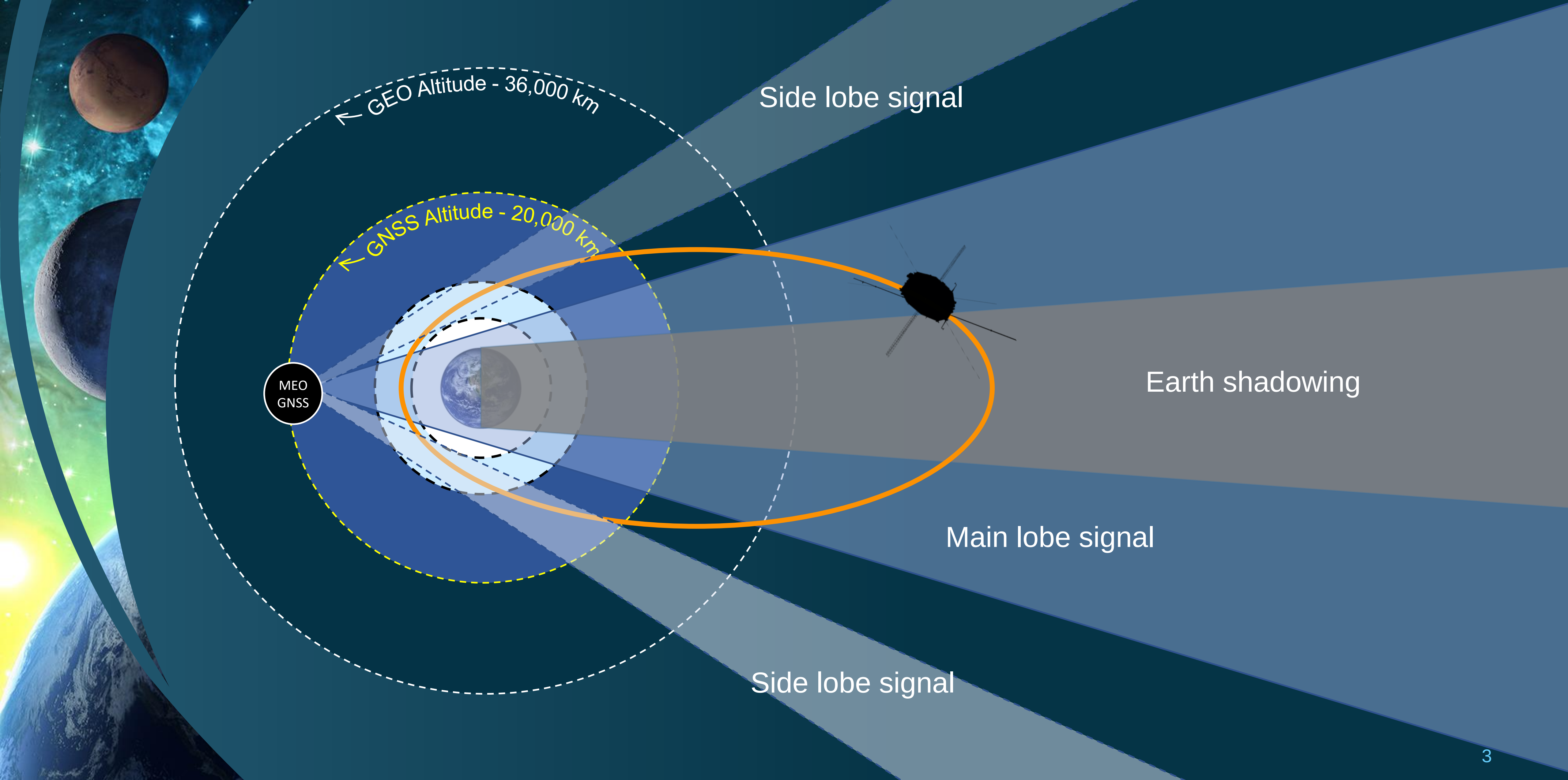
Italian Space Agency (ASI)

- **Co-PI**: Fabio Dovis
- **Project Manager**: Claudia Facchinetti
- **System Manager**: Mario Musmeci
- **Sponsor**: Alberto Tuozzi
- **Technical Team**: Luigi Ansalone, Giuseppe D'Amore, Gabriele Impresario

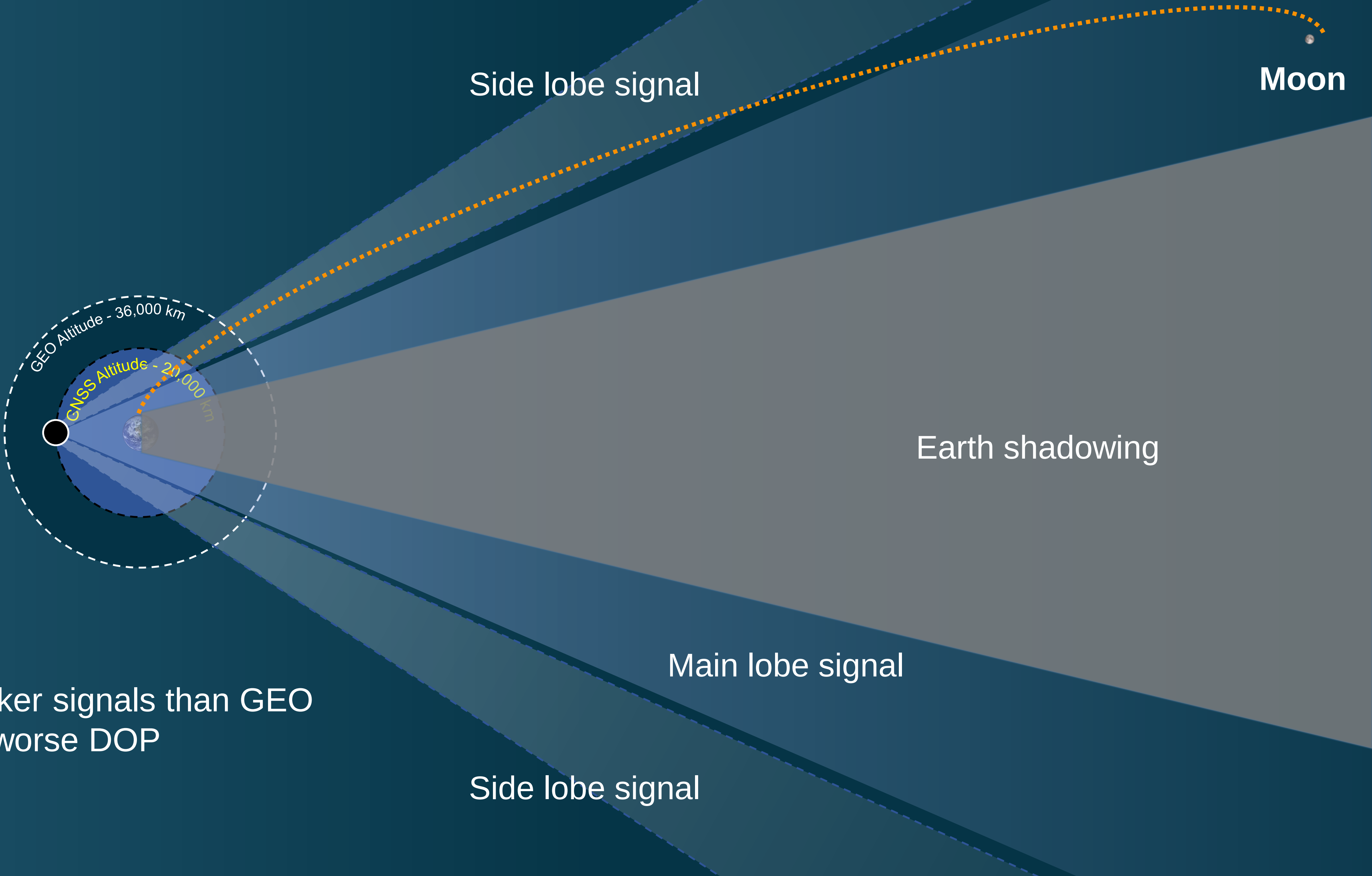
Qascom, S.r.l

- **Project Manager**: Samuele Fantinato
- **Systems Engineering Manager**: Efer Miotti
- **Technical Director**: Oscar Pozzobon

Signal Reception in the Space Service Volume (SSV)



Signal Reception **beyond** the Space Service Volume (SSV)



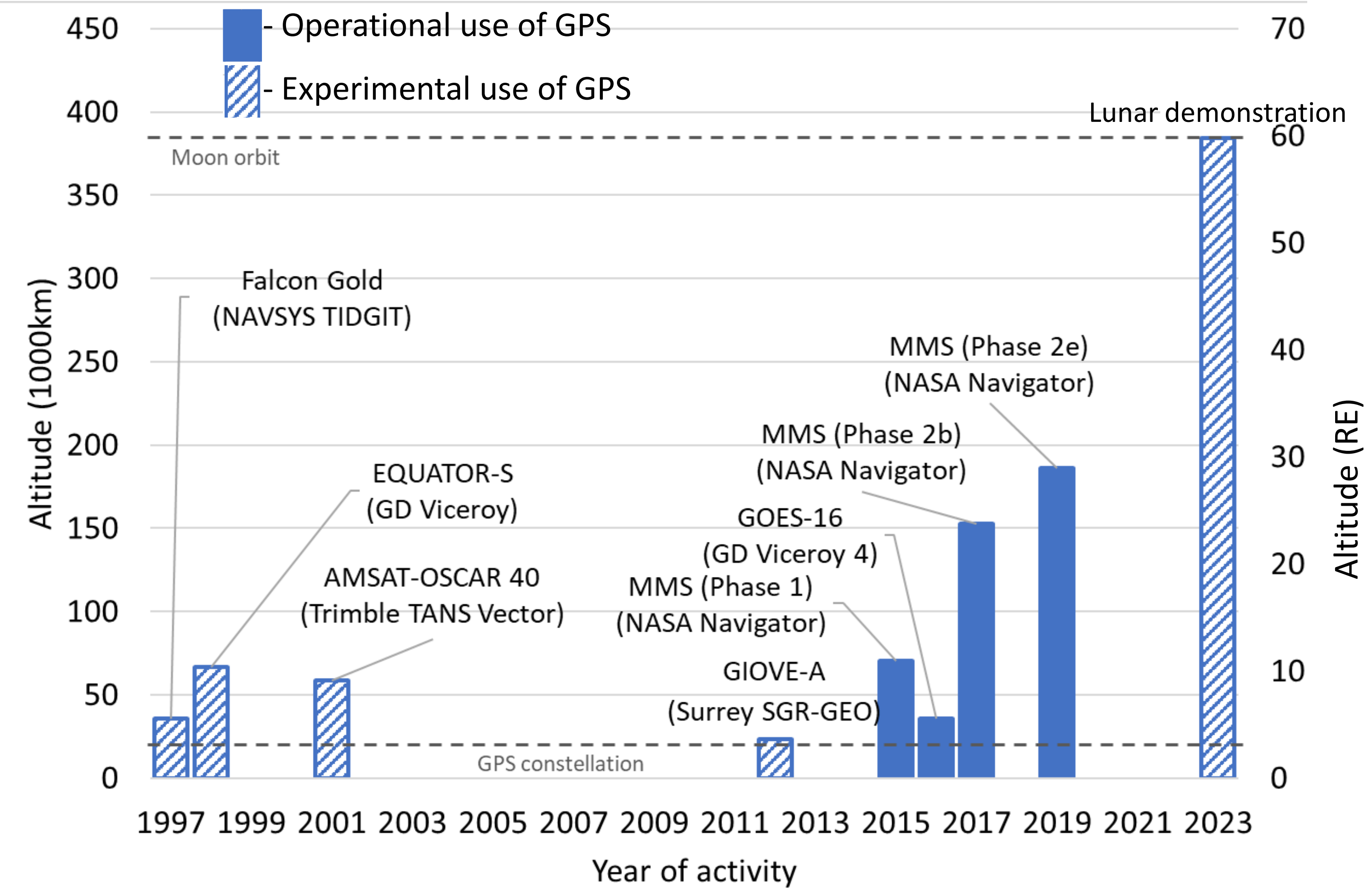
Challenges:

- >30x weaker signals than GEO
- 10–100x worse DOP

Development of High Altitude GNSS

Transition from experimentation to operational use, and move into cislunar space:

- **1990s**: Early flight experiments—Equator-S, Falcon Gold
- **2000**: Reliable GPS at GEO w/ bent pipe architecture
- **2001**: AMSAT OSCAR-40 mapped GPS main and sidelobe signals
- **2015**: MMS employed GPS operationally at 76,000 km
- **2016–2017**: GOES-16/17 employed GPS operationally at GEO
- **2019**: MMS apogee raise to 50% lunar distance
- **2023: Lunar demonstration**



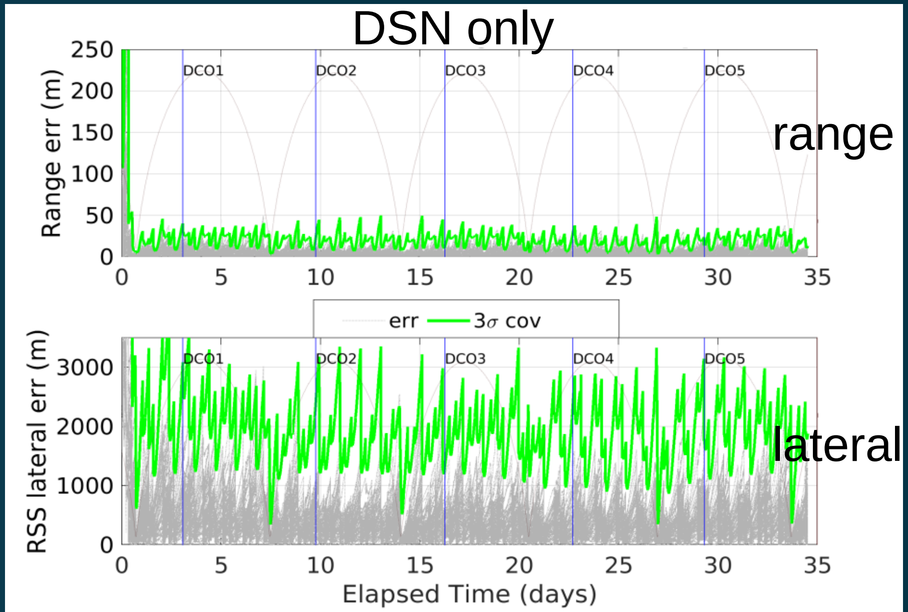
Lunar Gateway Study – Sep 2020

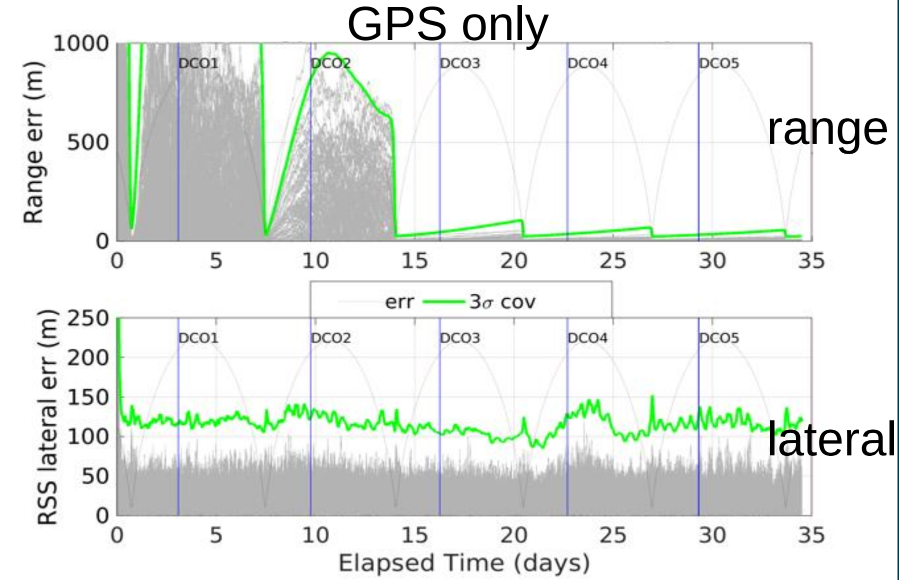
GPS Expected Performance

- Update to Feb 2019 preliminary study, both using MMS-calibrated models
- Position and velocity goals: 10 km and 10 cm/s, respectively
- Analyzed max OD error at the Data Cutoff (DCO) and at the final two perilunes and apolunes
- Observations:
  - GPS can provide greatly improved performance vs. DSN
  - GPS is real-time, on-board, without reliance on ground-based assets.

Max steady-state errors, crewed assumptions

	Case	DCO	Apolune	Perilune	All
Position [m]	**DSN**	1469.7	1326.4	319.8	2353.6
	GPS	**60.4**	**84.5**	**73.0**	**118.7**
	DSN+GPS	57.7	81.7	107.0	117.4





Lunar GNSS Phased Approach

Initial demonstrations

- Demonstrate lunar reception
- Opportunistic flights/technology
- Return evidence of performance
- Return raw data, lessons learned

- GNSS-only baseline demonstrations

LuGRE

First operational capability

- High-reliability unit
- High-accuracy clock
- Integrated into vehicle avionics
- Leverage demo data & lessons

- Utilize initial lunar PNT services

Commercialization

- Foster lunar rcvr commercial base
- Diversity of rcvr classes:
  - Flagship receivers
  - CubeSat/reduced SWaP
  - Integrated chipsets

- Leverage PNT signal compatibility: Earth-based GNSS + lunar PNT services

Broad Infusion

- GNSS is standard equipment
- Established, diverse rcvr base
- Part of diverse PNT solution

- Robust global PNT signal coverage from all sources

Relative use of signal sources

LuGRE Mission Overview

Mission

- NASA HEOMD payload for CLPS “19D” flight
- Joint NASA/Italian Space Agency mission
- “Do No Harm” class
- Firefly Blue Ghost commercial lander
- Transit+surface observation campaign
- Expected surface duration: one lunar day (~12 Earth days)

Payload objectives

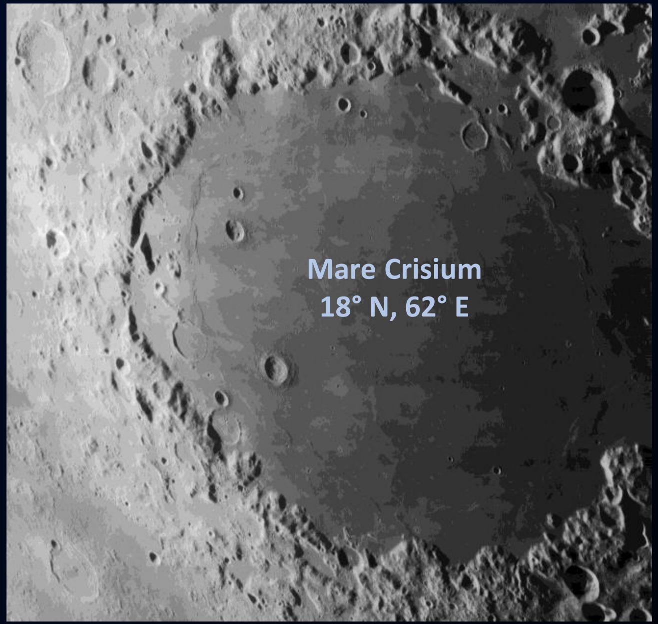
1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

Measurements

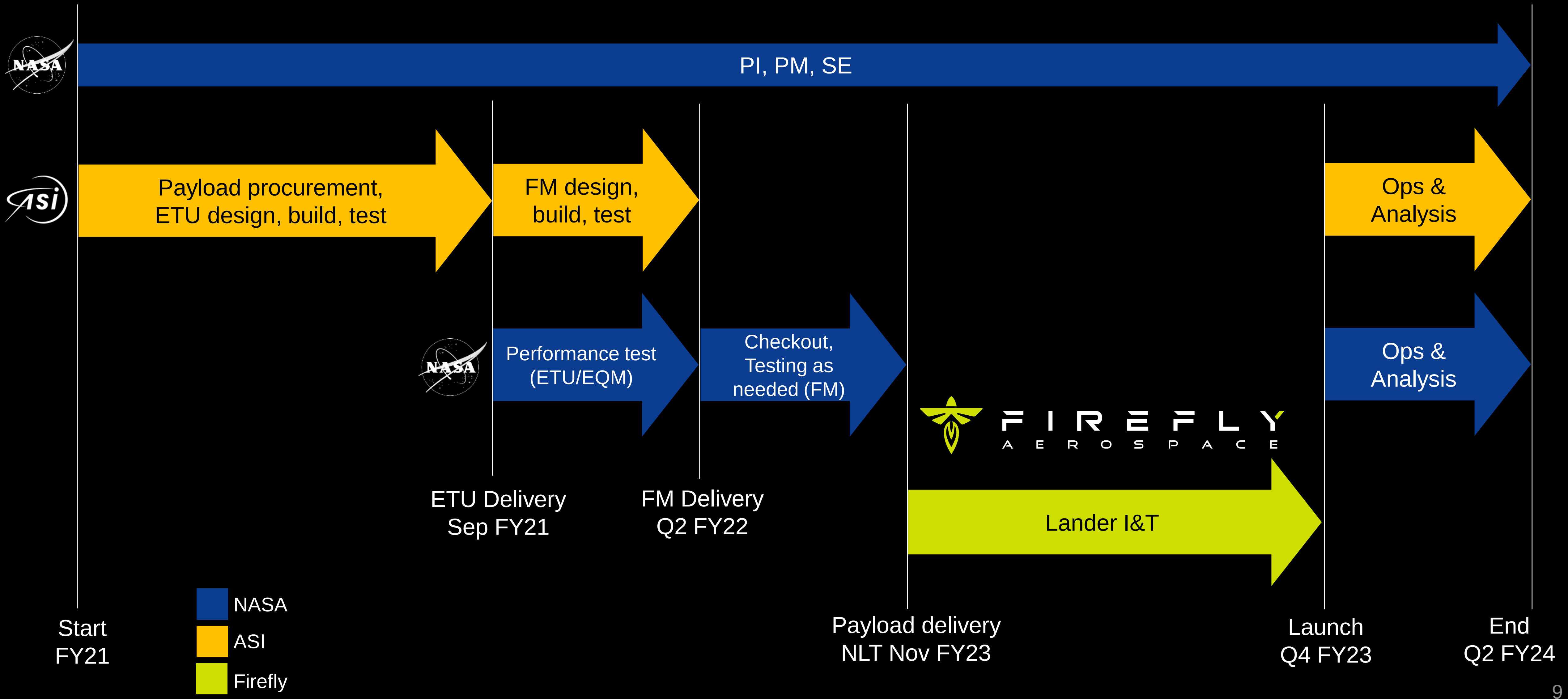
- GPS+Galileo, L1/L5 (E1/E5)
- Onboard products: multi-GNSS point solutions, filter solutions
- Observables: pseudorange, carrier phase, raw baseband samples

Utilization

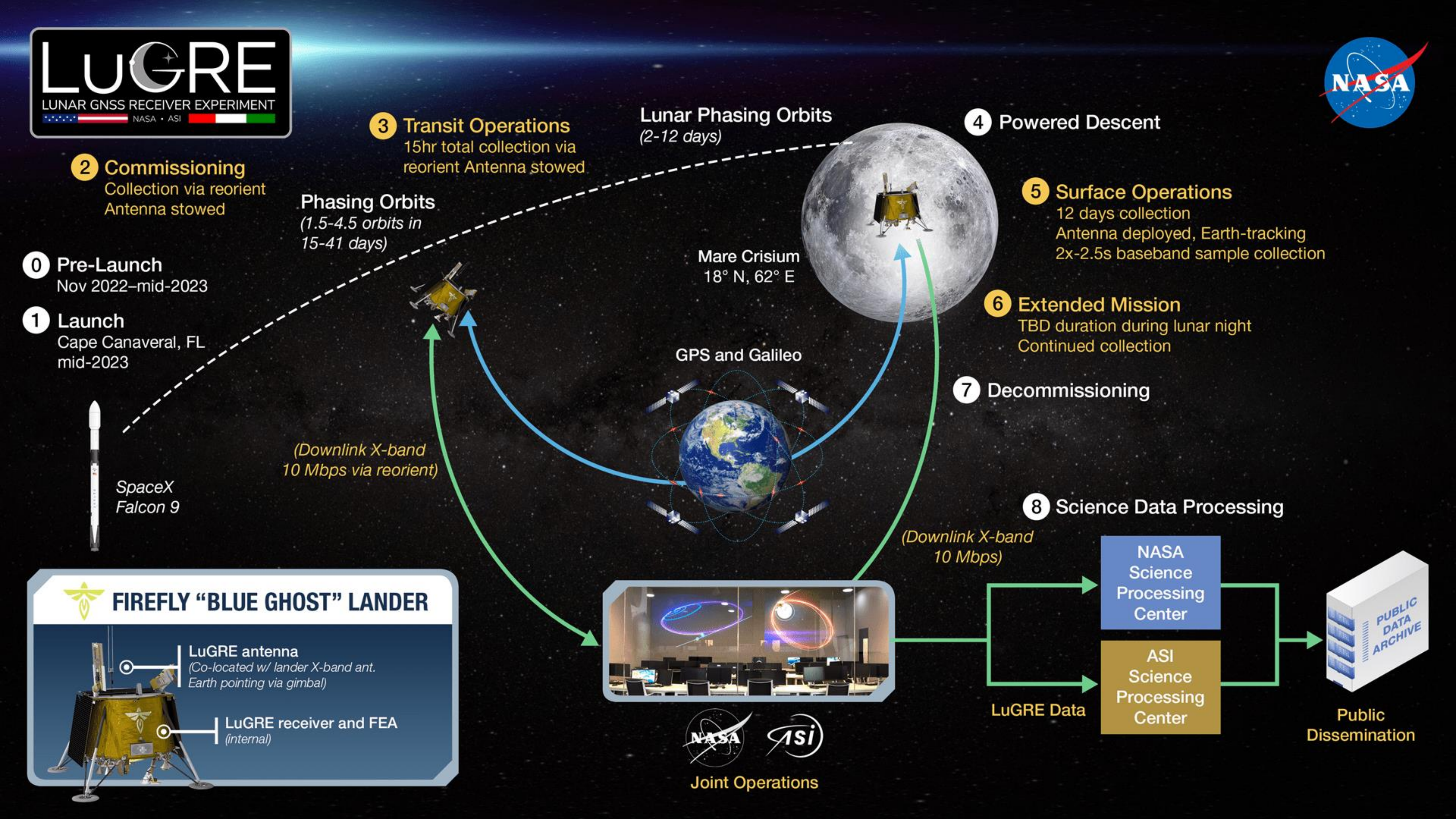
- Data + lessons learned for operational lunar receiver development
- Potential collaborative science: heliophysics, lunar geodesy
- Lunar human and robotic real-time onboard PNT



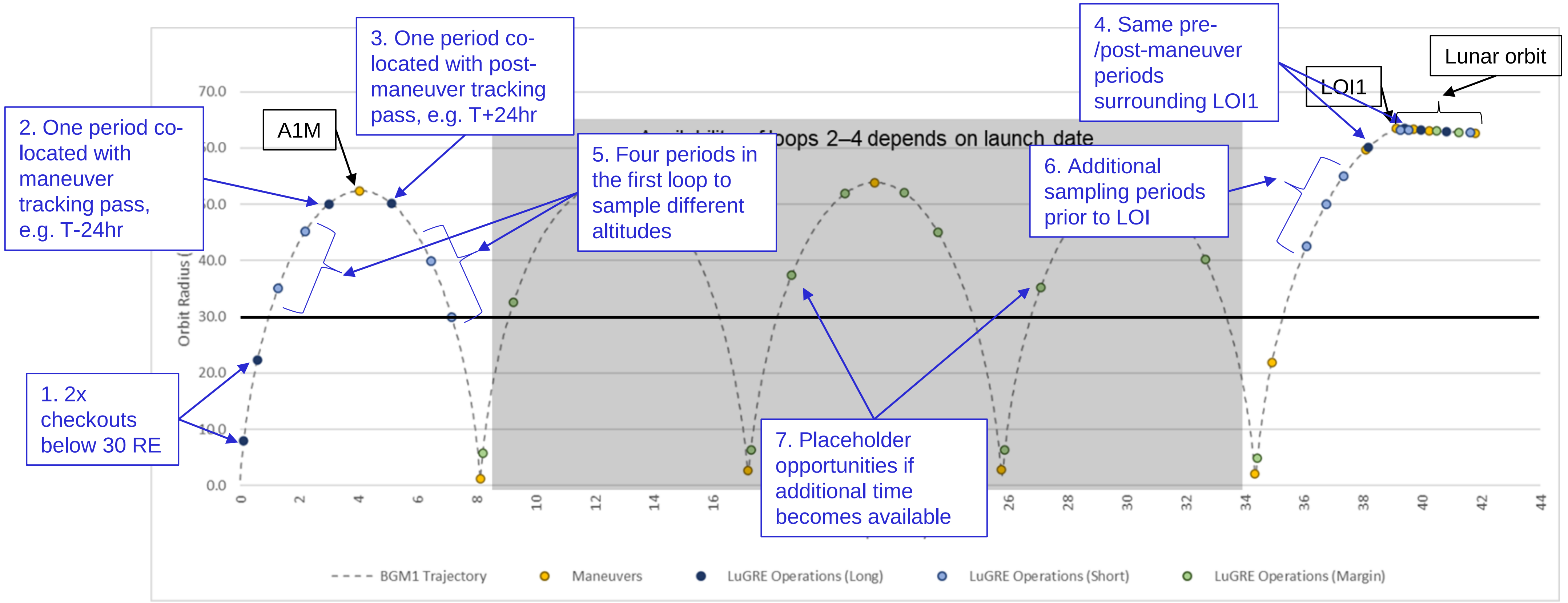
LuGRE Roles



PI, PM, SE
Payload procurement, ETU design, build, test
FM design, build, test
Ops & Analysis
Performance test (ETU/EQM)
Checkout, Testing as needed (FM)
Ops & Analysis
Lander I&T
ETU Delivery Sep FY21
FM Delivery Q2 FY22
Start FY21
NASA
ASI
Firefly
Payload delivery NLT Nov FY23
Launch Q4 FY23
End Q2 FY24

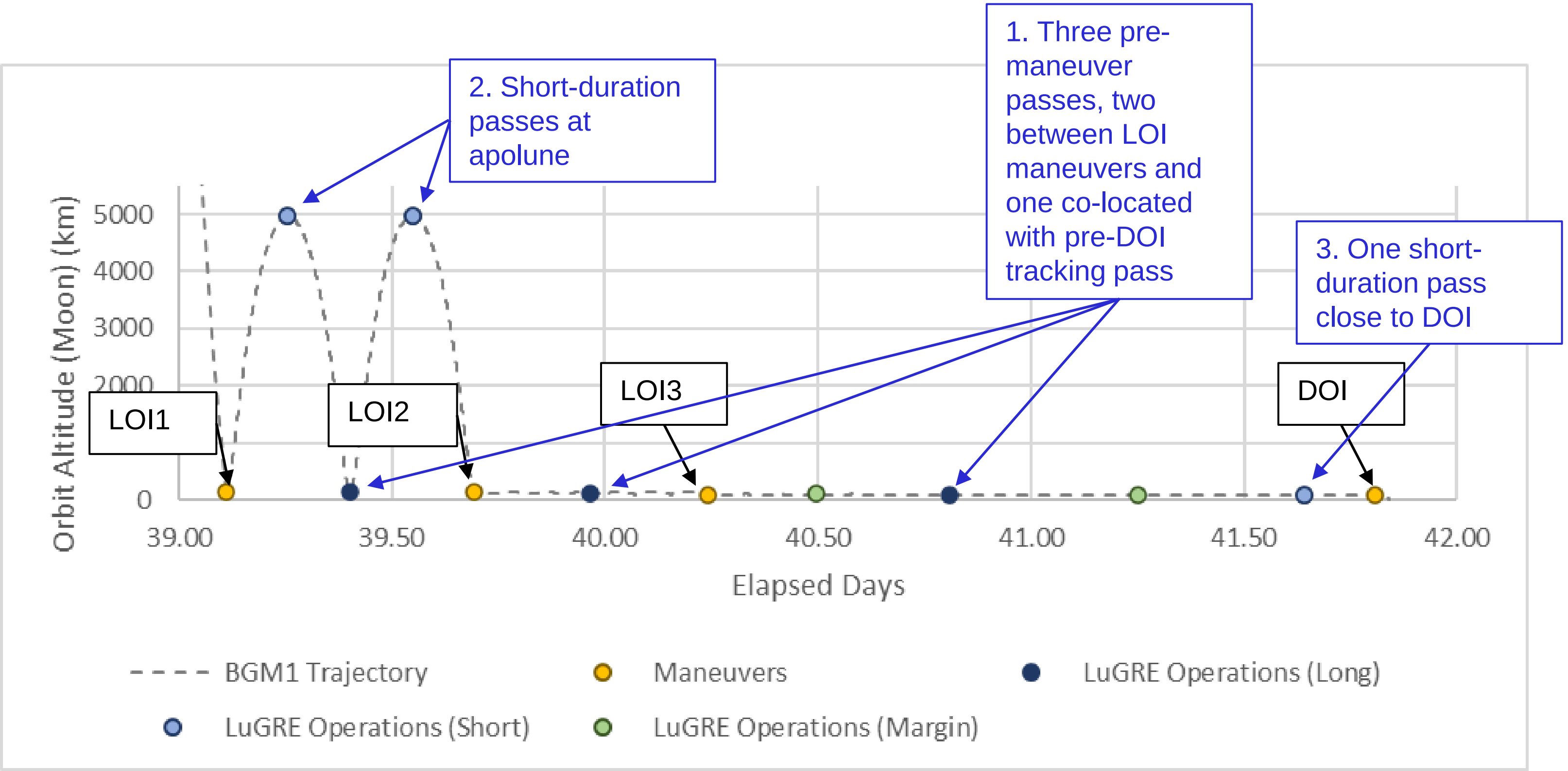

LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI
0 Pre-Launch
Nov 2022–mid-2023
1 Launch
Cape Canaveral, FL
mid-2023
SpaceX
Falcon 9
2 Commissioning
Collection via reorient
Antenna stowed
Phasing Orbits
(1.5-4.5 orbits in
15-41 days)
3 Transit Operations
15hr total collection via
reorient Antenna stowed
Lunar Phasing Orbits
(2-12 days)
4 Powered Descent
5 Surface Operations
12 days collection
Antenna deployed, Earth-tracking
2x-2.5s baseband sample collection
6 Extended Mission
TBD duration during lunar night
Continued collection
7 Decommissioning
Mare Crisium
18° N, 62° E
GPS and Galileo
(Downlink X-band
10 Mbps via reorient)
(Downlink X-band
10 Mbps)
8 Science Data Processing
NASA
Science
Processing
Center
ASI
Science
Processing
Center
LuGRE Data
PUBLIC
DATA
ARCHIVE
Public
Dissemination
Joint Operations
FIREFLY "BLUE GHOST" LANDER
LuGRE antenna
(Co-located w/ lander X-band ant.
Earth pointing via gimbal)
LuGRE receiver and FEA
(internal)

Transit Operations Plan (Earth→Moon Transit)



- Initial “Full” operations plan, showing all features
- Total overall operations duration in transit is limited to 15hr as baseline due to limited ACS propellant available for Earth pointing
- Baseline (blue) operations have long (60 min) and short (42 min) durations; 18 total. Focus is altitude sampling and pre-/post- maneuver nav demo.
- Opportunistic (“margin”) operations (green) are pre-planned and can be activated if additional time becomes available

Transit Operations Plan (Lunar)



- Lunar orbit portion: 5000km x 100km → 250km x 100km → 100km circular
- Total duration: 3 days
- Data collection focuses on key areas: demonstrate nav for maneuvers; leading into DOI; at perilune/apolune

LuGRE Payload

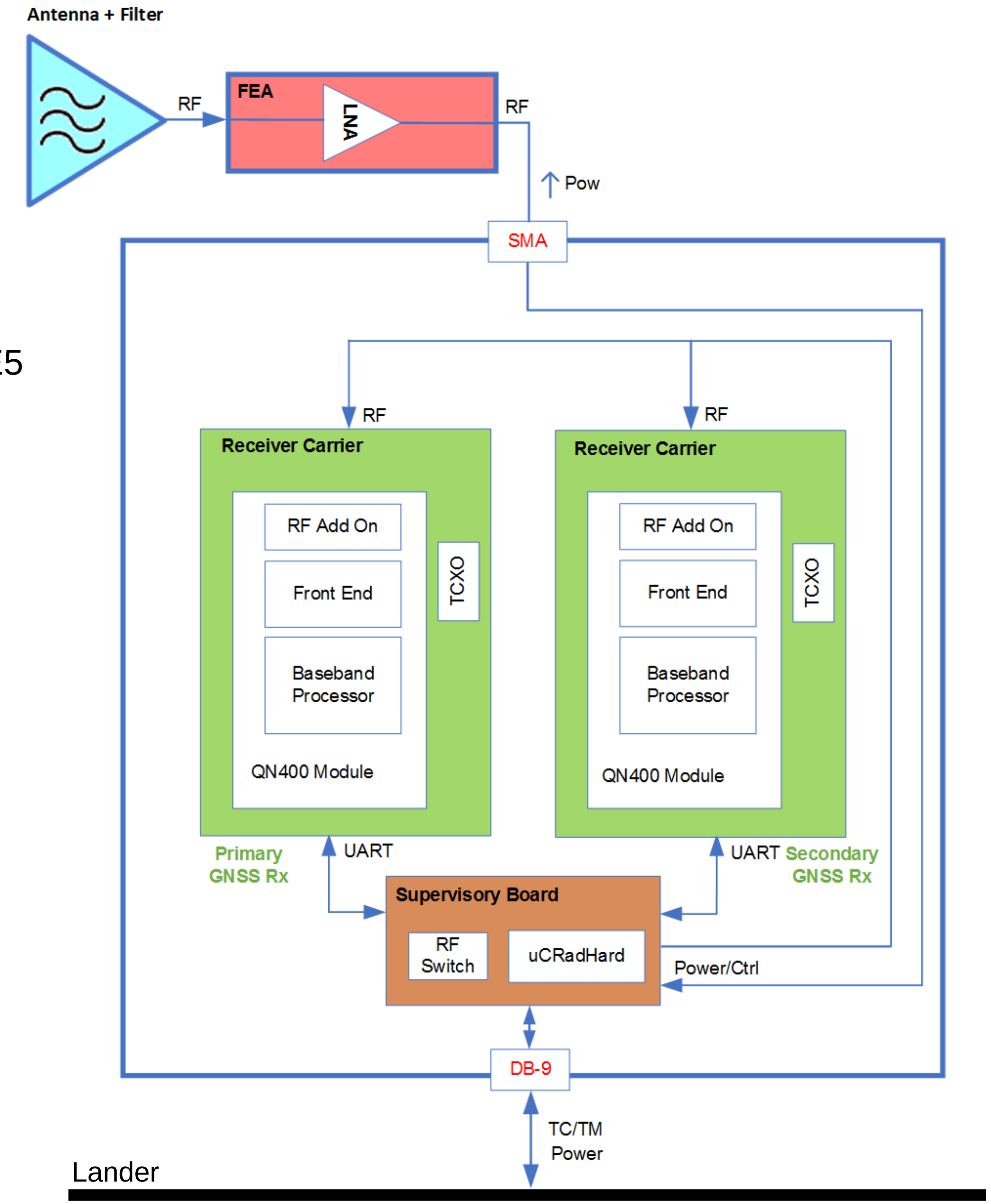
Payload characteristics

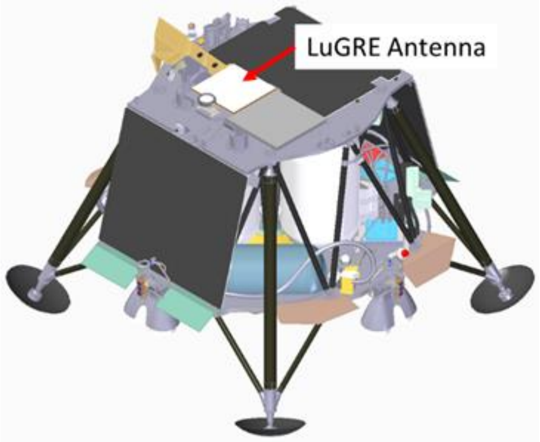
1. High-altitude GNSS receiver
- Qascom receiver, GPS+Galileo L1/E1 + L5/E5
- Based on QN400 flight heritage
- Cold redundant configuration
- Mass: 1.24 kg
- Power: 14 W

2. Low-noise amplifier (LNA)
- Mass: 0.85 kg
- Power: 0.7 W

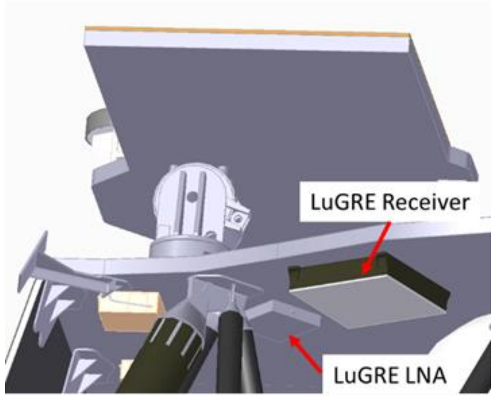
3. High gain L-band antenna + filter
- Requires Earth pointing for GNSS reception
- 14 dBi peak gain, 10deg FOV
- Mass: 2.2 kg
- Power: 0 W (passive)

Total resource allocations
- Mass: 4.64 kg
- Power: 14 W





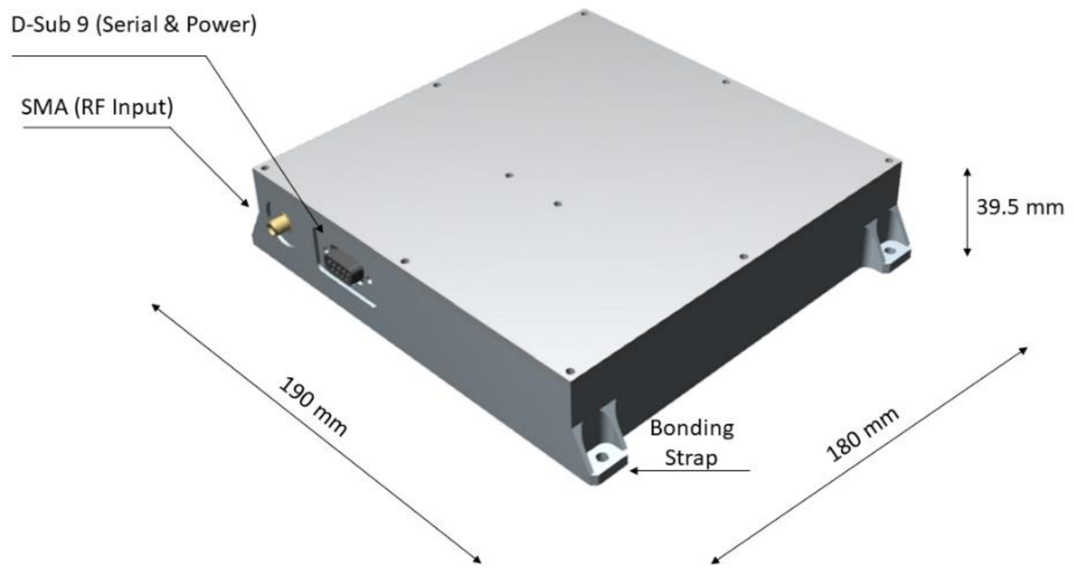
Lander Top Deck, External View



Lander Top Deck, Internal View

Receiver

Parameter	Value
Mass	1.24 kg
Power	14 W (operating)
Envelope	19.0 x 18.0 x 3.95 cm
Operating Temperature Range	-35°C to 50°C
Signal Reception	GPS L1 C/A and L5 Galileo Open Service E1 and E5a
Weak Signal Acquisition and Tracking Threshold	< 23 dB-Hz
Capabilities	• Lunar-capable extended Kalman filter • Capture of raw IQ samples • Navigation ephemeris and aiding data upload via telecommand
Data Product Output	• Least-squares point solutions • Extended Kalman filter solutions with covariance • Pseudorange observations • Doppler • Carrier phase observations • Tracking status & C/N0 • Raw IQ samples

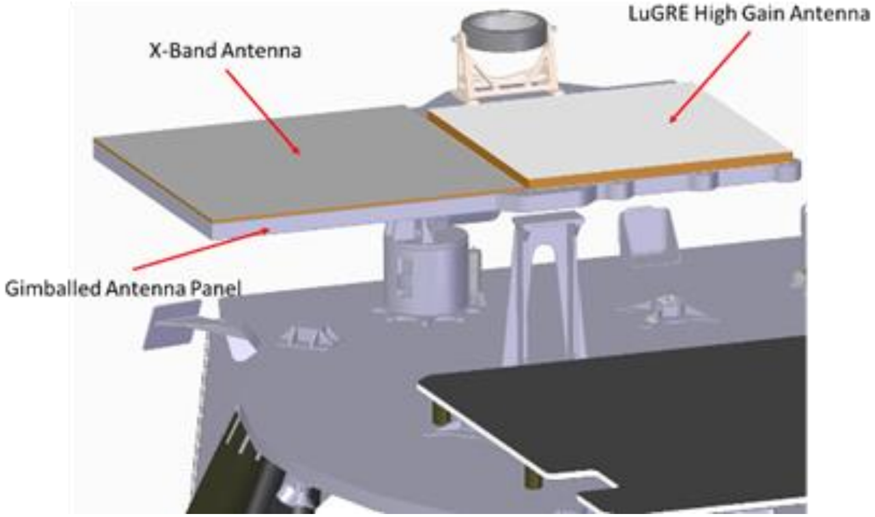


- Developed by Qascom, S.r.l. for ASI
- Based on Qascom QN400 flight heritage
  - Suborbital sounding rockets
  - Ohio University Bobcat-1 LEO CubeSat
- SDR architecture
- Dual-receiver cold-redundant configuration to mitigate single-event radiation effects

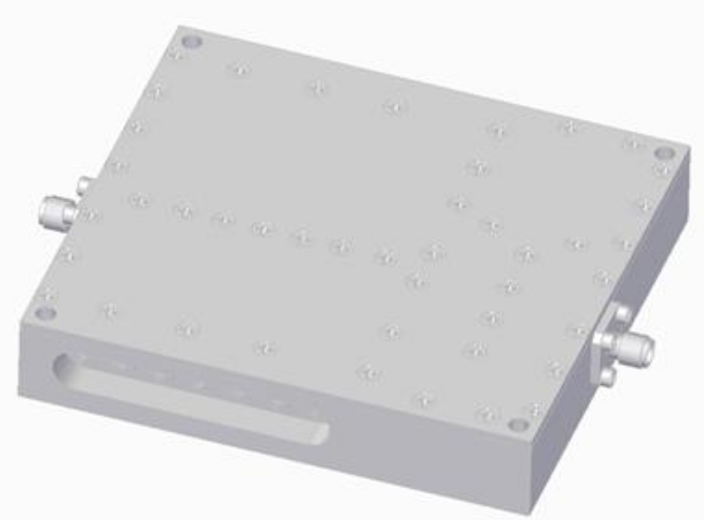
HGA/LNA

Parameter	Value
Mass	2.2 kg
Power	passive
Envelope	43.0 x 43.0 x 2.00 cm
Operating Temperature Range	-145°C to 125°C
Antenna Type	Passive Planar Antenna Array
Polarization	RHCP
Gain	≥ 14 dBi
Working Band 1	1575.42 +/- 12.276 MHz (L1/E1)
Working Band 2	1176.45 +/- 10.230 MHz (L5/E5a)
Connector	1x SMA

HGA



Parameter	Value
Mass	0.85 kg
Power	0.7W
Envelope	9.3 x 10.2 x 1.8 cm
Operating Temperature Range	-35°C to 50°C
1st Band:	1575.42 +/- 12.276 MHz (L1/E1)
2nd Band:	1176.45 +/- 10.230 MHz (L5/E5a)
Noise Figure	≤ 3 dB
Connector	2x SMA



LNA

LuGRE Outcomes

Characterize the GNSS signal environment	Characterize navigation performance	Share collected data	Facilitate adoption of capability

Characterize the GNSS signal environment

- GPS+Galileo, L1+L5, E1+E5a
- Signal availability
- DOP
- C/N_0
- Observables
  - Pseudorange
  - Carrier phase
  - Doppler
- Raw baseband I/Q samples
- Transmit antenna patterns
- Multipath, surface environment

Characterize navigation performance

- Point solutions
- Onboard Kalman filter states
- Time to first position fix
- Formal errors, convergence
- Comparison to independent sources (lander, LRR)
- Application of GGTO

Share collected data

- GNSS receiver developers
- LuGRE science partners
- NASA missions (Artemis, Gateway, science)
- Commercial landers
- International space agencies
- GNSS community
- Science community
- Public

Facilitate adoption of capability

- Raw data availability
- LuGRE team reports + papers
- Calibration of lunar GNSS simulation models
- Application to future mission navigation studies
- Lessons learned to GNSS hardware and software developers

*Specific investigations are coordinated via LuGRE Science Team

Mission Science

LuGRE Science Team structure:

LuGRE Science Team

Primary Science Teams

NASA PI Office

LuGRE PI: Joel Parker
Deputy PI: Lauren Schlenker
Science team members

ASI PI Office

LuGRE Co-PI: Fabio Dovis
Science team members

Research Partners (pending)

- NASA and ASI researchers
- Academia
- Industry
- NavSAS at Politecnico di Torino

Public

Driving investigations:

Objective 1

- Measure the signal strength throughout the mission and empirically evaluate link budget model.
- Determine signal availability throughout the mission.
- Measure Doppler-shift and Doppler-rate profiles throughout the mission.
- Measure pseudorange from visible satellites during all planned operations periods.

Objective 2

- Calculate and characterize least-squares multi-GNSS point solutions throughout the mission where sufficient signals are available.
- Calculate and characterize Kalman filter based navigation solutions onboard throughout the mission.
- Compare onboard navigation solutions to external sources (e.g., ground-based measurement processing, planned trajectory, Blue Ghost navigation solution).
- Characterize position, velocity, and time uncertainty and convergence properties throughout mission.

Objective 3

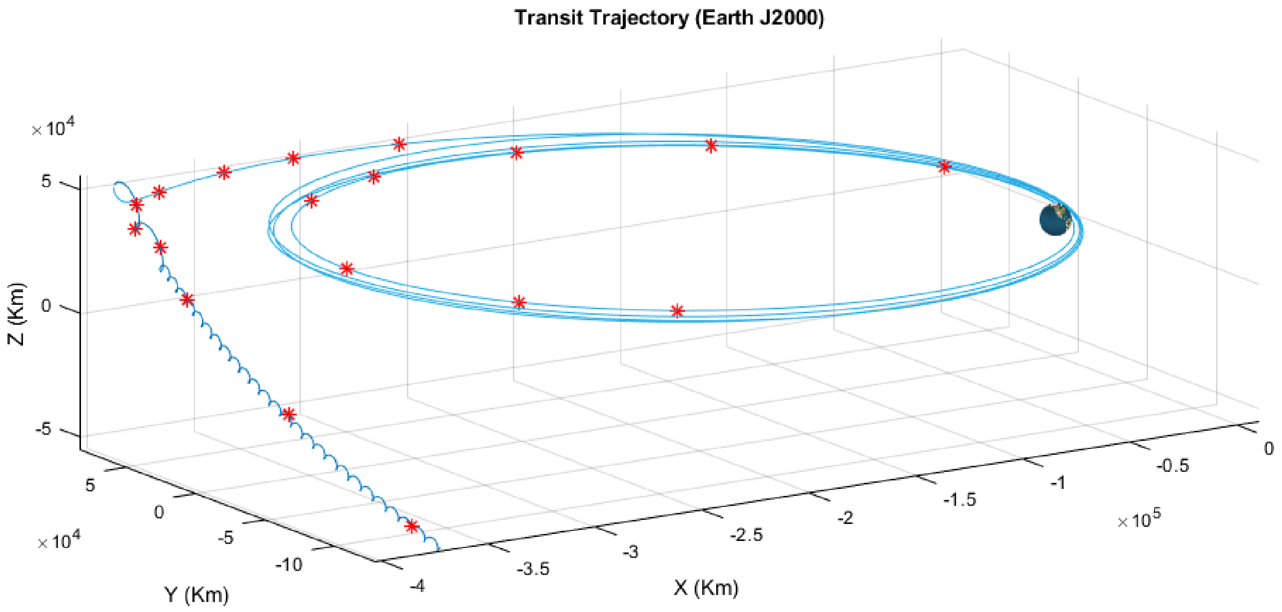
- Process GNSS observables (e.g., Doppler, pseudorange) with ground-based tools to predict achievable onboard navigation performance.
- Calibrate ground models with LuGRE data and utilize to predict achievable navigation performance for future missions.

Opportunities for external research partners to get involved in science definition.

Mission Performance Analysis

- Initial analysis of expected mission performance
- Focus: visibility (transit + lunar surface), real-time filter navigation performance
  - Baseline 18x operations periods during transit, continuous surface operations
  - L1 signal only, L5 simulation is future work
  - Receiver threshold 23 dB-Hz
- Tools/data:
  - NASA Goddard Enhanced Onboard Navigation System (GEONS)
  - Accessed via GEONS Ground MATLAB Simulation (GGMS)
  - High-fidelity GPS model calibrated with MMS flight data, GPS ACE transmit antenna patterns and available patterns from ground data
  - Publicly-available Galileo orbits, ESA 2019 antenna pattern
  - Firefly trajectory, Haigh-Farr simulated HGA pattern
- Link budget model:

$$C/N_0 = P_T + G_T(\phi,\theta) - 20\log\left(\frac{4\pi d}{\lambda_{L1}}\right) + G_R(\phi,\theta) - L_{pol} - 10\log(kT_{sys}) - R_{loss}$$

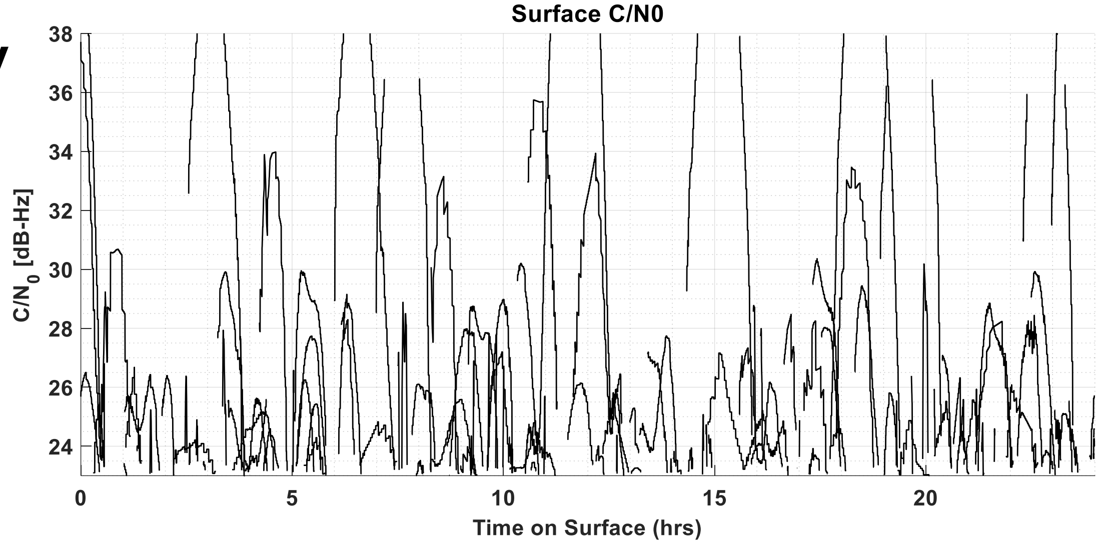


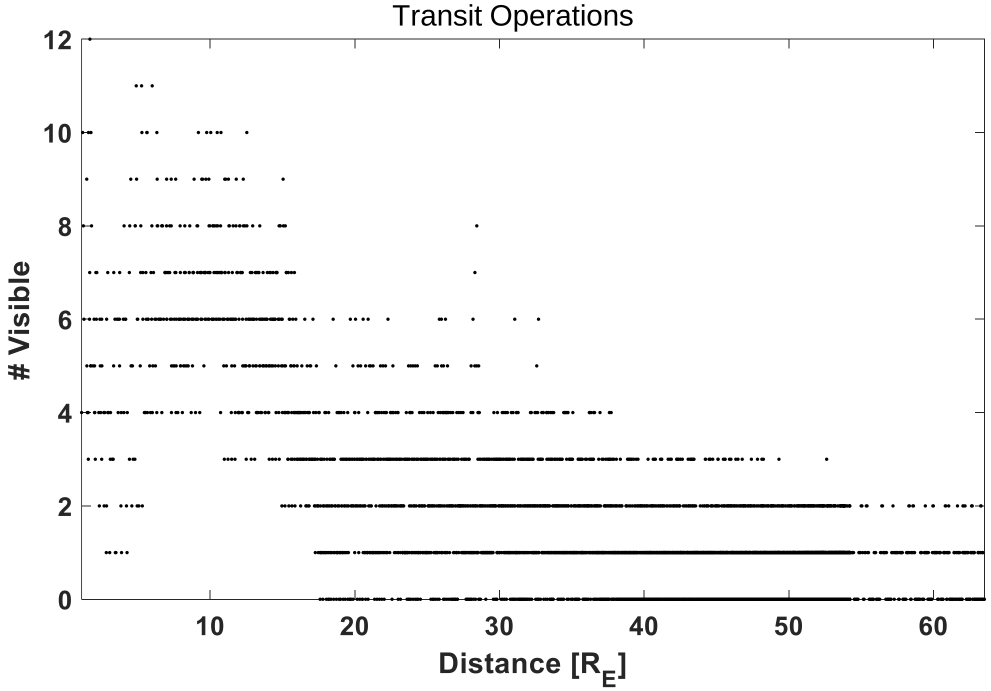
Link budget parameters

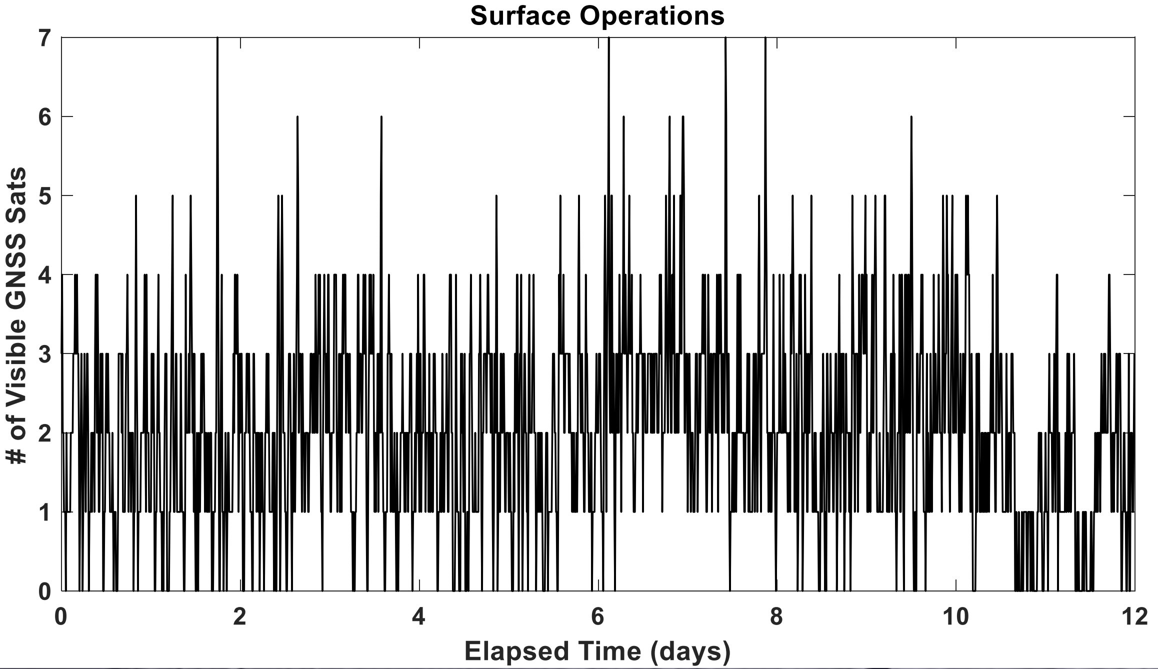
Parameter	Value
Receiver Implementation Losses R_{loss}	0.9 dB
System Temperature T_{sys}	295 K
Polarization Losses L_{pol}	3 dB
P_T (GPS Block IIR)	17.3 dBW
P_T (GPS Block IIR-M)	18.8 dBW
P_T (GPS Block IIF)	16.2 dBW
P_T (GPS Block III)	18.8 dBW
$P_T + G_T(\text{peak})$ (Galileo)	11 dBW
$G_R(\text{peak})$	16 dBW

Mission Performance: C/N0, Visibility

- Signal visibility extends to 60+ RE and is available on lunar surface.
- Average visibility at Moon is 2 SVs
- 4+ SV visibility achieved often in transit and at Moon (>10% of time)
  - Indicates occasional point solution availability
- Visibility is nearly all GPS, likely due to conservative Galileo assumptions
- C/N0 peaks >30 dB-Hz for main lobes, ~26 dB-Hz for side lobes

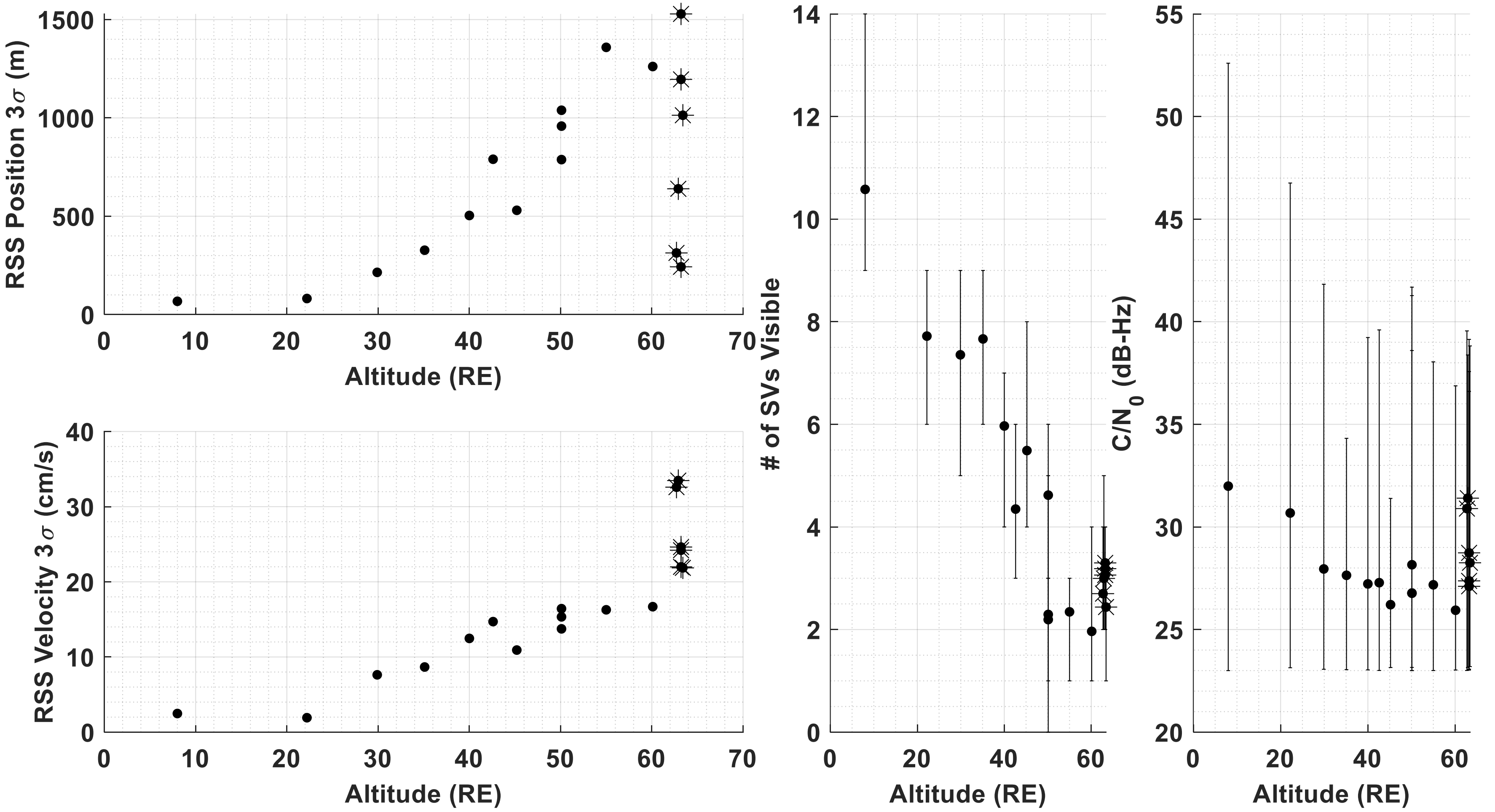






Mission Performance: Transit Navigation

- NASA GEONS transit operations navigation performance simulation
- RSS position/velocity 3σ covariance at end of operational arc (42 min or 60 min)
- Results generally a function of number of satellites visible as altitude increases.
- Final 6 periods in are in lunar orbit. Highly variable accuracy indicates sensitivity of solution to visibility and geometry.



Mission Performance: Sample Capture

- Analysis by ASI with support by Politecnico di Torino
- Purpose: Assess feasibility of GNSS signal acquisition from raw IQ samples collected over a limited time window (ms)
- Result: Minimum coherent integration time needed to successfully acquire the signal, for different C/N0 and limiting the search space to Doppler bins
- Nd = number of Doppler bins in search space

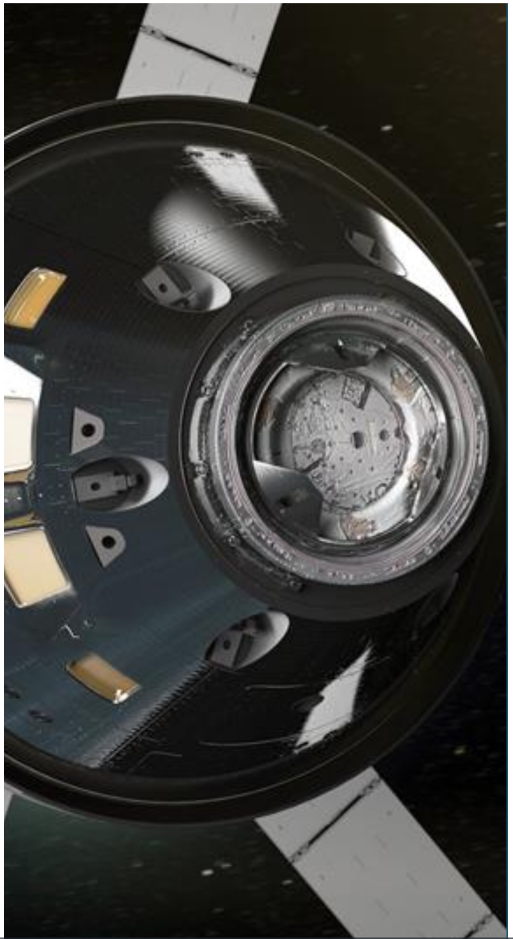
C/N0 (dB-Hz)	(ms) (Full SS)	(ms) (Nd = 5)	(ms) (Nd = 3)
36.4	6	4	4
32.2	8	6	6
27.2	55	45	45
24.0	120	90	90
21.9	105	100	100
20.2	175	160	160
18.6	415	370	230

Conclusions

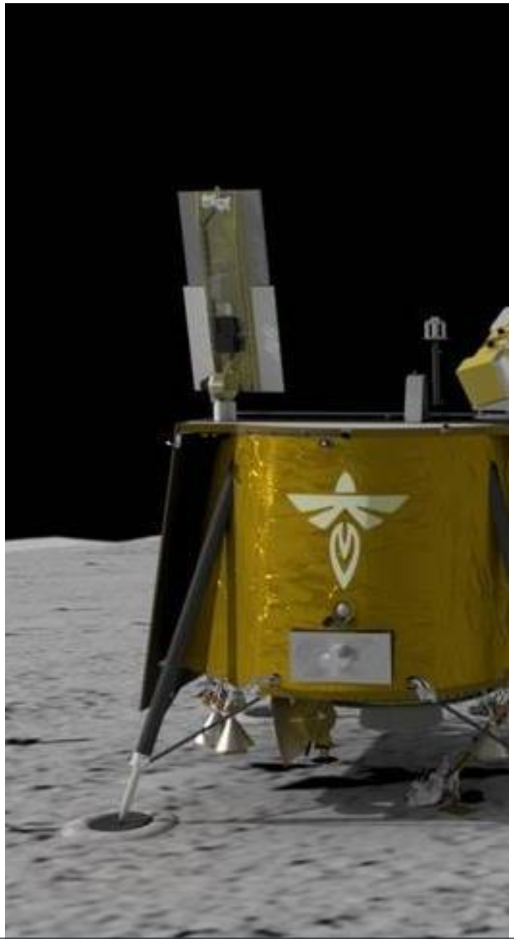
- LuGRE is a joint NASA/ASI project that will demonstrate GNSS-based PNT in transit to the Moon and on the lunar surface.
- LuGRE will fly a Qascom-designed weak-signal multi-GNSS receiver and high-gain antenna to receive GPS and Galileo signals in L1 and L5 bands.
- Initial performance simulations indicate a high degree of confidence in meeting the LuGRE science objectives to characterize the signal environment, perform navigation at the moon, and apply the results to future developments.
- **LuGRE will create an initial public dataset with the intention to jump-start development of GNSS-based navigation at the moon.**

Backup

What’s Next

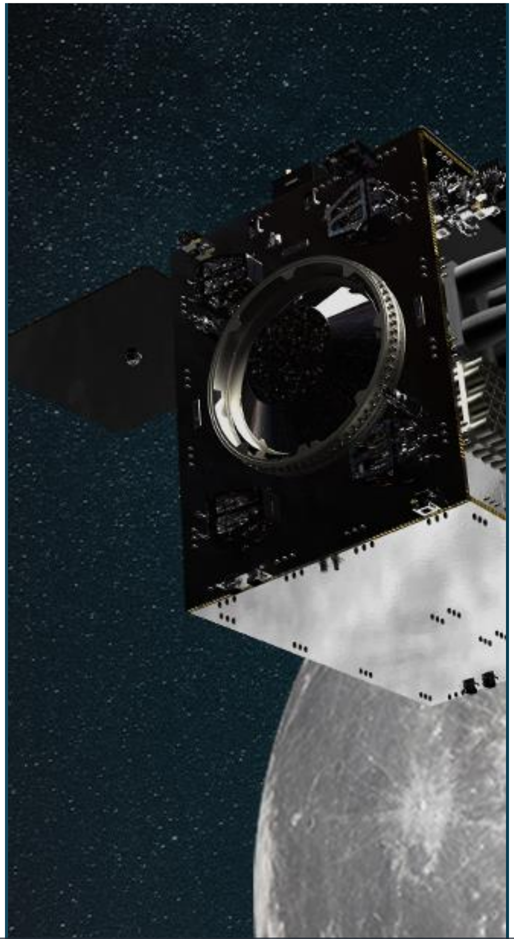


Artemis-1
(LEO receiver)
2022

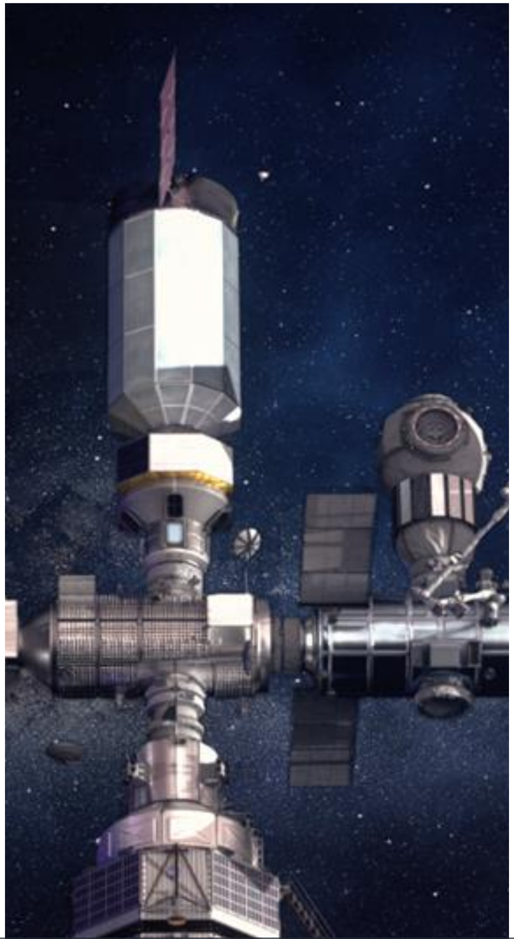


LuGRE

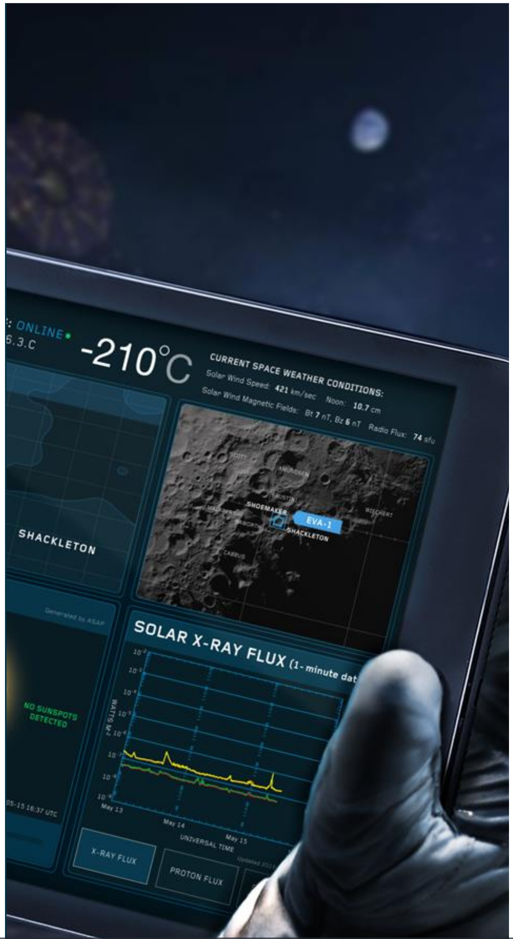
2023



Lunar Pathfinder
(ESA)
2024



Gateway Payloads



LunaNet

LuGRE Project Organization (NASA)

Lander
Firefly

Launch Vehicle

Payload
ASI (Italian Space Agency)

Payload Vendor
Qascom

External interfaces

SCaN Program (NASA HQ)
JJ Miller/PSC, Jason Mitchell/ACNT

HQ Technical Advisors
Lisa Valencia/Overlook
AJ Oria/Overlook

Principal Investigator
Joel Parker/595

Science Team
Deputy PI: Lauren Schlenker/595
Co-PI: Fabio Dovis/ASI
Frank Bauer/FB-ACS

Mission Manager
Benjamin Anderson/450.2

PM Support (RA/CM)
GSFC 450.2

ISE
Stephen McKim/597

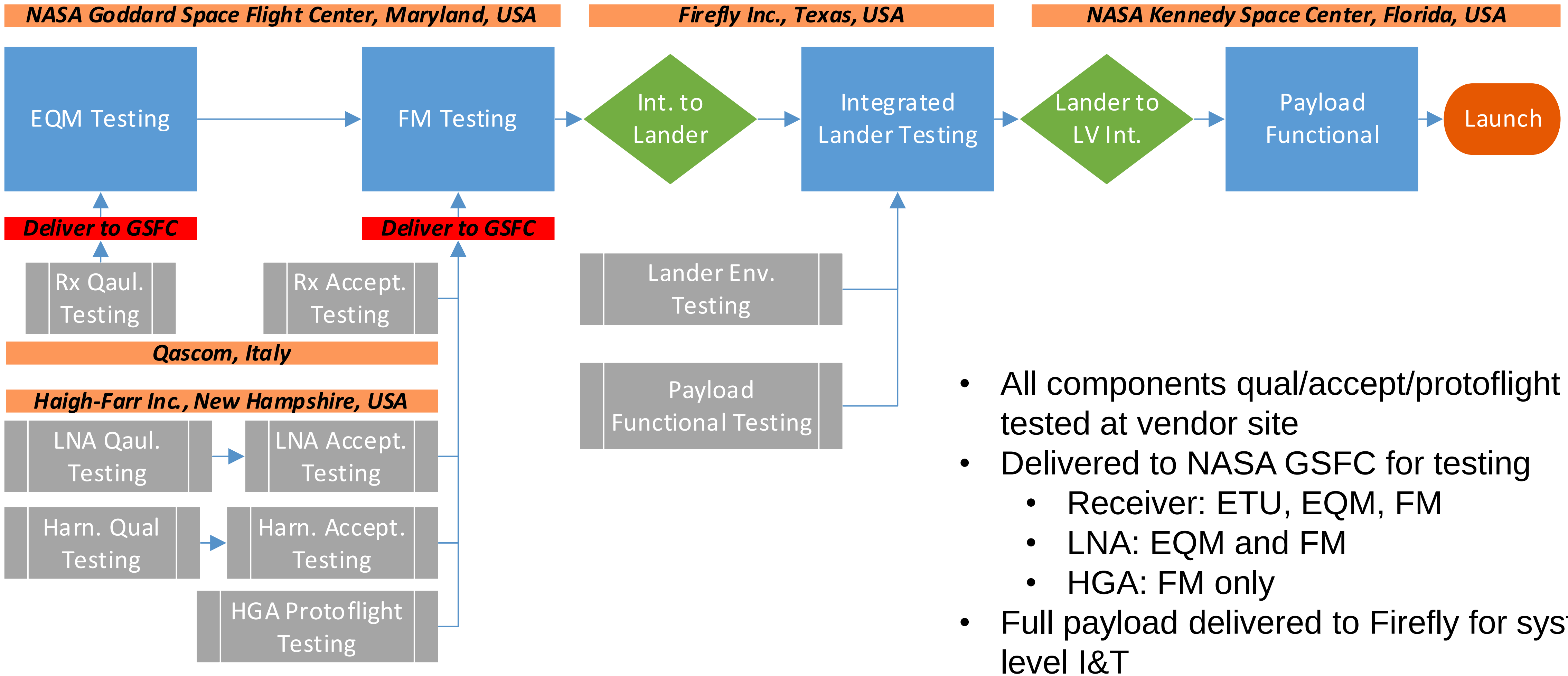
Electrical
GSFC Code 596

Perf Testing
GSFC Code 596

Env Testing
GSFC Code 540

NASA/HQ	NASA/GSFC
Firefly	ASI

Integration & Test



- All components qual/accept/protoflight tested at vendor site
- Delivered to NASA GSFC for testing
  - Receiver: ETU, EQM, FM
  - LNA: EQM and FM
  - HGA: FM only
- Full payload delivered to Firefly for system-level I&T
- Firefly delivers to launch site